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# FINAL REPORT

1 October 1995 to 30 June 1997

GRANT: F49620-95-1-0351-P00002

*John M. Mulvey*

*Robert J. Vanderbei*

*Princeton University*

## Final Report - 1 October 1995 to 30 June 1997

*John M. Mulvey  
Robert J. Vanderbei  
Princeton University*

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### Summary

The primary aim of the project was to develop practical models and algorithms for robust optimization. Towards this goal, we have improved the efficiency of linear and nonlinear algorithms for solving robust optimization models. By specializing the ordering of the key matrix ( $ADA^t$ ), we have reduced the computational times for factorizations -- by over 100 times for larger examples. The largest LP problem solved to date (with 16,000 scenarios) consists of approximately 1 million constraints and 1.7 million variables. More importantly, the run time is a linear function of the number of scenarios. Hence the primary bottleneck for solving large examples is the amount of available computer memory. This result applies to a spectrum of planning problems since the ordering routine does not take advantage of the matrix structure within a scenario.

Over the past several years, we have continued to specialize the large-scale optimization algorithms. Also, we have worked on the selection of the scenarios for robust optimization so that the number of scenarios is kept to a reasonable level. The use of out-of-sample precision tests have been designed and tested for evaluating the confidence in the recommendations of the models.

### Accomplishments/New Findings

Robust optimization problems grow quickly as a function of the number of scenarios. However, we like to include a wide range of possible scenarios to model the stochastic parameters in a realistic fashion. Thus, we are faced the tradeoff of numerical efficiency (or even solvability) versus modeling accuracy. It is therefore important for us to have the ability to solve problems with a moderate number of scenarios (at least several hundred to several thousand). We demonstrated that the Diagonal Quadratic Approximation (DQA) method is highly effective in this environment. We showed that direct solvers can also be implemented on parallel-processing computers by parallelizing the factorization routine. This result might apply to the more general area of large scale optimization, but more research is needed to determine the degree of generality of the results.

We specialized the factorization routine for the structure inherent in robust optimization models using the split variable formulation. We developed a preordering routine that greatly reduces the time to factor the ( $ADA^t$ ) matrix -- a key step in the interior point codes. The preordering is called *tree dissection* and takes advantage of the structure of the split-variable robust optimization model. This approach is considerably more efficient than the traditional multiple min-degree ordering routine (over 50-100 times faster). We continue to test this approach with large-scale test problems.

## Personnel Supported

- Faculty:
  - \* John M. Mulvey
  - \* Robert J. Vanderbei
- Graduate Students:
  - \* Robert Rush
  - \* Michael T. Tapia

## Publications

- *Submitted but not yet accepted*

J. M. Mulvey, F. Glover, D. Bai, "Integrative Population Analysis for Better Solutions and 'What-If' Analysis in Industrial Engineering Applications," Princeton University Report SOR-96-9, 1996.

J. M. Mulvey, F. Glover, D. Bai, "Improved Approaches to Optimization via Integrative Population Analysis," Princeton University Report SOR-95-25, 1995.

R.J.Vanderbei, "LOQO: An Interior Point Code for Quadratic Programming," Princeton University Report SOR-94-15, 1994, submitted to *Mathematical Programming*.

- *Accepted but not yet published*

A. Berger, J. Mulvey, E. Rothberg, and R. Vanderbei, "Solving Multistage Stochastic Programs using Tree Dissection," *SIAM Journal on Optimization*, to appear.

A. Berger, J. Mulvey, "Asset and Liability Management for Individual Investors," to appear in World Wide Asset and Liability Modeling by W. T. Ziemba and J. M. Mulvey (eds.), Cambridge University Press, 1996.

J. M. Mulvey, A. Eric Thorlacius, "The Towers Perrin Global Capital Market Scenario Generation System: CAP:Link" to appear in World Wide Asset and Liability Modeling by W. T. Ziemba and J. M. Mulvey (eds.), Cambridge University Press, 1996.

J. Mulvey, D. P. Rosenbaum and B. Shetty, "Parameter Estimation in Stochastic Scenario Generation System," Princeton University Report SOR-96-15, to appear in *Journal of Mathematical Finance*.

J. M. Mulvey, "Financial Planning via Multi-Stage Stochastic Optimization," Princeton University Report SOR-94-09, 1994, to appear as a feature article in *ORSA Journal on Computing*.

• **Published**

P. Fishburn, P. Schwander, L.A. Shepp, and R.J. Vanderbei. The discrete Radon transform and its approximate inversion via linear programming. *Discrete Applied Math*, 75, 1997, 39-61.

D. Bai, T. Carpenter, J. Mulvey, "Making a Case for Robust Optimization Models, *Management Science*, 43, 7, July 1997, 895-907.

C. Maranas, I. Androulakis, C. Floudas, J. Mulvey, "Solving Stochastic Control Problems in Finance via Global Optimization, *Journal of Economics Dynamics and Control*, 21, 1997, 1405-1425.

J. M. Mulvey, B. Shetty, and D. Rosenbaum, "Strategic Financial Risk Management and Operations Research: A Review," *European Journal of Operations Research*, 97, 1997, 1-16..

J. M. Mulvey, W. Ziemba, "Asset and Liability Allocation in a Global Environment," *Finance*, North Holland Publishing Company, 1995, 435-463.

J. M. Mulvey "It Always Pays to Look Ahead," *Balance Sheet*, 4, 4, Winter 1995/6.

J. M. Mulvey, J. Birge, "Stochastic Programming," in Mathematical Programming for Industrial Engineers, by Avriel and B. Golany (eds.), Marcel Dekker, Inc., New York, 1996, 543-574.

J. M. Mulvey, "Generating Scenarios for The Towers Perrin Investment System," *Interfaces*, 1996, 1-21.

J. M. Mulvey, "Solving Robust Optimization Models in Finance," in *Proceedings of the IEEE/IAFE 1996 Conference on Computational Intelligence for Financial Engineering*, 1996 1-13.

J. M. Mulvey, F. Glover, and K. Hoyland, "Solving Dynamic Stochastic Control Problems in Finance Using Tabu Search with Variable Scaling," in *Proceedings of the Meta-Heuristics International Conference MIC-95*, Kluwer Academic Publishers, 1995, 429-448.

L.A. Shepp and R.J. Vanderbei. "The complex zeros of random polynomials. *Transactions AMS*, 347(11):4365--4384, November 1995.

R. J. Vanderbei. "A probabilistic formula for the concave hull of a function," *Ann. Prob.*, 23:2014--2021, October 1995.

C. Helmberg, F. Rendl, R.J. Vanderbei, and H. Wolkowicz. "An interior point method for semidefinite programming." *SIAM J. Optimization*, 6:342--361, May 1996.

Y. Ikura and R.J. Vanderbei. "Application of integer programming to petroleum tank truck scheduling problems. In *Proceedings of the Seventh RAMP Symposium*, pages 79--89, Kyoto, Japan, November 1995.

## Books

R.J. Vanderbei, **Linear Programming**. Kluwer Academic Publishers. October 1996.

## Book Chapters

R.J. Vanderbei. Discrete space markov processes. in Large Deviations for Performance Analysis, pages 499--514. Chapman-Hall, 1995.

## Interactions/Transitions

### *a. Participation/presentations at meetings, conferences, seminars, etc.*

#### *J. M. Mulvey*

September 5, 1996, Invited Lecture on "Creating Customized Derivative Securities via Multi-Period Asset Liability Systems", Financial Options Research Center: 9<sup>th</sup> Annual Conference, London, England.

July 17, 1996, Invited Lecture on "Optimization Methods for Selecting Risks in the Reinsurance Marketplace", Renaissance Re-Insurance, Inc., Bermuda.

27 June, 1996, Invited Lecture on "Asset Liability Management Systems for Long-Term Investors", Society of Actuaries Annual Meeting, Colorado Springs, Colorado.

May 6, 1996, "Robust Optimization for Groundwater Remediation", Washington, D.C.

March 24, 1996, Keynote Address: "Solving Robust Optimization Models in Finance", IEEE/IAFE Conference on Computational Intelligence for Financial Engineering", New York, New York.

February 14, 1996, Invited Talk on "Robust Optimization", National Academy of Sciences Review Committee, Washington, D.C.

January 8, 1996, "MB1 Survey: Solving Large-Scale Robust Optimization Models", 5<sup>th</sup> CSTS Conference on Computer Science and Operations Research, Dallas, Texas.

December 12, 1995, Invited Lecture on "Large-Scale Asset Liability Management Systems", Falcon Asset Management, Baltimore, Maryland.

December 4, 1995, Invited Lecture on "Applications of Robust Optimization", Austin, Texas.

October 29-November 1, 1995, INFORMS National Meeting, New Orleans, Louisiana.

Invited lecture on "Solving Stochastic Financial Problems by a GRG Tabu Search Method" (with F. Glover and M. Tapia).

Invited lecture on "Temporal Preferences for Long-Term Financial Planning" (with A. Berger and M. Tapia).

Invited lecture on "Robust Optimization Models in Telecommunications" (with D. Bai).

October 13, 1995, "Boulder, Colorado, "Integrative Asset/Liability Systems for Long Term Investors, Joint Workshop: Operations Management/Finance and Economics Division and U.S. West.

October 11, 1995, Baltimore, Md, "Comparing Asset and Liability Management Models, USF&G Company and Falcon Asset Management Corporation.

October 9, 1995, Burlington, Vt, "Applications of Robust Optimization," Invited lecture at the School of Engineering.

September, 20-22, 1995, Nicosia, Cyprus, Two invited lectures "Asset Liability Models for Long Term Investors," International Conference on Deregulation of Emerging Markets, Sponsored by European Union, and Workshop on Financial Engineering.

### ***R. J. Vanderbei***

INFORMS, New Orleans, Oct 29 - Nov 1, 1995. Computational Optimization, Session Chair.

INFORMS, New Orleans, Oct 29 - Nov 1, 1995. Invited Talk. LOCO: An Extension of LOQO to Convex Programming (with Bing Yang).

INFORMS, Washington DC, May 5 - 8, 1996. Invited Talk. Solution Strategies for Robust Optimization (with John Mulvey and Ed Rothberg).

INFORMS, Washington DC, May 5 - 8, 1996. Sponsored Talk. A Truck Dispatching Scheduler (with Yoshiro Ikura).

#### **• Consultative and Advisory Functions**

- \* AT&T Bell Labs. Contacts: Peter Fishburn and Larry Shepp, Used interior-point technology to determine crystal imperfections. New technology is called discrete tomography. See patent below.
- \* Gary Johnson, JWAC (540) 653-1490.
- \* ORTEC Consultants BV, Gouda, The Netherlands. Contact: Fred Meemskerk. Use LOQO for financial applications.

#### **• Transitions**

- \* Worked with Tamra Carpenter (Bellcore) and Tony Cox and Fred Glover (U.S. West) to develop models for designing robust and self-healing telecommunications networks (*John M. Mulvey*).
- \* Distribution of the robust telecommunications model to researchers at other institutions conducting work on stochastic optimization. Lectures at various professional meetings (*John M. Mulvey and Robert J. Vanderbei*).
- \* Worked with Silicon Graphics, Inc. (SGI) to develop the tree dissection algorithm (*John M. Mulvey*).
- \* Distribution of the robust STORM model and other test cases to researchers at other institutions conducting work on stochastic optimization. Lectures at various professional meetings (*John M. Mulvey*).
- \* Meetings with many firms who have become interested in robust optimization (e.g. Bellcore, US West, Towers Perrin, USF&G) and faculty members such as Leon Lasdon, Fred Glover and their students (*John M. Mulvey*).

- \* LOQO has been installed at numerous commercial and educational sites (e.g. Bellcore, Bell Labs, SGI, Fujitsu) (*Robert J. Vanderbei*).
- \* LOQO has been used by Larry Shepp at Bell Labs for Discrete Submicroscopic Tomography (*Robert J. Vanderbei*).
- \* LOQO has been distributed to numerous researchers around the world (e.g. Georg Bock, Romesh Saigal, Chris Floudas) (*Robert J. Vanderbei*).

### **New Discoveries**

Continue to develop the preordering procedure called tree dissection, which greatly reduces the time needed to factor the  $ADA'$  matrix. This factorization is a time consuming process in interior point codes. This approach is over 50 times as fast as the traditional approach (multiple min-degree ordering), with the improvement greater for larger problems.

Patent Pending, P.Schwander, L.A. Shepp, and R.J. Vanderbei. Apparatus and method for tomography of microscopic samples. U.S. Patent Pending. Invention concerns microscopic tomography, wherein probabilities of occupancy of individual lattice sites within a crystal are estimated. Application to the examination of the internal structure of semiconductors.